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THE EFFECTS OF SPACE DEBRIS ON SOLAR PROPULSION



March 1991

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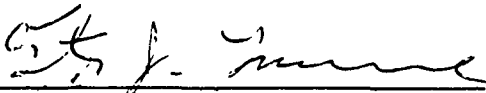
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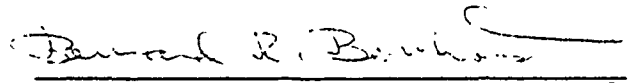
FOREWORD

This interim report was submitted on completion of this task of JON: 305500R7 by the OL-AC PL/RKAS Branch, at the Phillips Laboratory (AFSC) (formerly Astronautics Laboratory), Edwards AFB CA 93523-5000. OL-AC PL Project Manager was Lt Tim Lawrence.

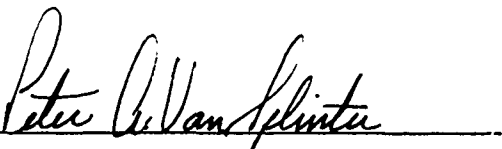
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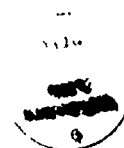


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INTRODUCTION

Solar Propulsion Concept

For the solar propulsion concept (SPC) there are two energy focusing concentrators integrated with a solar flux-absorbing thruster and a single fuel tank. This solar powered propulsion system can make Low Earth Orbit (LEO) to Geosynchronous Earth Orbit (GEO) missions more profitable. The SPC will double the Isp of conventional orbital transfer vehicles (1000 sec for a hydrogen working fluid at 3000 K), and consequently double the payload moved to GEO with half the propellant used by current systems.

Two large solar concentrators gather, focus, and concentrate approximately 1500 kW into their respective thruster cavities to produce the required energy to heat the working fluid (hydrogen) to 3000 Kelvin to produce thrust. Note that for the calculations in this paper hydrogen is the working fluid for the thrusters and helium, the inflatable for the concentrators. See Figure 1.

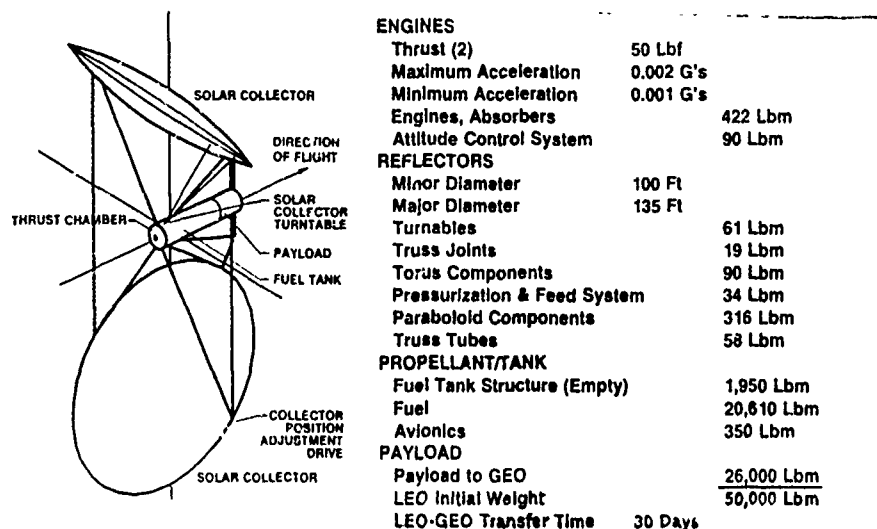


Figure 1. Solar Propulsion System

The two inflatable concentrators are the focus of our concern about orbital debris flux. The SPC's two off-axis parabolic concentrators are designed to have an approximate 40-meter major diameter by 30-meter minor diameter to cover the projected sun diameter. The concentrators are pressurized double concavo-convex lenses that have a hollow interior and a thin film skin. Each concentrator looks like a giant clam shell (Fig. 1) with an approximate projected area of 100 square meters (Ref. 1, p. 3).

The thruster is a dual cavity, dual nozzle device designed to capture the solar energy from both collectors. The single working fluid is heated and expanded indirectly by conductive heating from a solar heated material in the cavity atmosphere. Without igniting the fluid, thrust is produced in the propulsive nozzle and the gas expelled. Table 1 defines some of the solar propulsion parameters (Ref. 1, p. 2-3).

| Table 1. Solar Propulsion Parameters |
|---|
| Thrust = 100.0 lbf |
| Isp = 1000 sec (Hydrogen @ 3000 K) |
| Gross weight (to LEO) = 50,000 lbm |
| Reflector projected area = 1000 m ² |
| Volume inside both reflectors = 175,000 ft ³ |
| Required pressure in reflectors = 2.46×10^{-4} psi |
| Delivery weight (to GEO) = 28,000 lbm |
| Estimated trip time = 30 days |

DEBRIS ISSUES

To clarify the complexity of the problem, it is necessary to provide some basic definitions and explanations. This paper addresses two types of space debris hazards: meteoroids and orbital debris.

Natural meteoroids are a natural space debris hazard that is not usually present in an earth orbit. Meteoroids come from a variety of possible sources including asteroids, comets, and the moon. Meteoroids do not enter an Earth orbit because they remain in a orbit similar to that of their parent body.

Artificial (orbital) space debris is man-made material orbiting the earth. Large pieces of artificial debris include spent rocket stages, nonoperational payloads, payload separation hardware, and satellite breakup fragments (Ref. 2, p. 1). Micro-size objects consist of paint particles from spacecraft surfaces, aluminum oxide and other propellant particles or droplets. Figure 2 breaks down the percentage of debris in each of the categories.

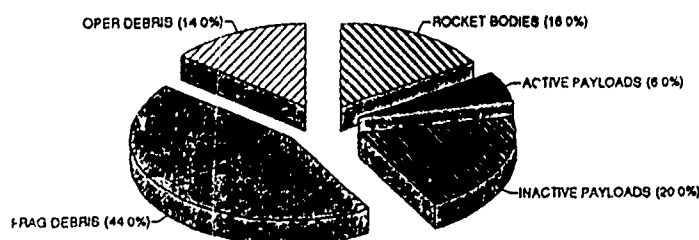


Figure 2. On-Orbit Population (Ref. 3, p. 5)

In general, natural meteoroids have greater relative velocities (20 km/s) than orbital debris (10 km/s) (Ref. 4, p. 4). At any one time there are 200 kg of meteoroids within 2000 km of the earth's surface. Most of these particles have an average 1-mm diameter. The flux of natural meteoroids varies in time with the sun's solar activity cycles (Ref. 4, p. 1).

On the other hand, there is 3,000,000 kg of orbital debris within the same 2000-km altitude band. Over 7,000 objects presently tracked by NORAD comprise most of this orbital debris mass (Ref. 4, p. 4). These mass distributions can be deceiving because there is

another 3.5 million man-made fragments orbiting the earth whose mass is only about 1000 kg of that total (Table 2). This means that of the 3.535 million man-made objects orbiting the earth in LEO, only 7,000 (0.2%) are tracked by NORAD. NORAD presently has the capability of tracking particles that are 10 cm or greater in diameter (Ref. 4, p. 3-4).

Particles with diameters between 1 cm and 10 cm comprise another 0.5% of this 3.525 million population. Powerful optical telescopes (like MIT's ground telescopes) can track particles with diameters as small as 1 cm on a nonoperational basis.

The remaining 99.3% of these 3.525 million man-made objects in LEO have diameters of less than 1 cm (Ref. 4, p. 4). Although current ground-based sensors can not track these objects, flux and probability curves are generated by extrapolations and impact data taken from recovered satellites and space vehicles. Table 2 shows the orbital debris population and percentages by diameter and mass.

| Table 2. Estimated Artificial Debris Propulsion (Ref. 4, p. 4) | | | | |
|--|----------------|------------|-----------|--------|
| Size | No. of Objects | Percentage | Mass (kg) | % Mass |
| > 10 cm | 7,000 | 0.2 | 2,999,000 | 99.97 |
| 1-10 cm | 17,000 | 0.5 | 1,000 | 0.03 |
| < 1 cm | 3,500,000 | 99.3 | ----- | ----- |
| TOTALS | 3,524,500 | 100.0 | 3,000,000 | 100.00 |

There is a small size range in which the number of meteoroids is significantly larger than the number of man-made debris. At present meteoroid populations are significantly higher in the 0.1 to 1-mm diameter range. Some predictions show that man-made debris will outnumber meteoroids in this size range around the turn of the century (Ref. 4, p. 15-16).

The large numbers of nontrackable debris makes calculating debris flux on the concentrators a dilemma. Although debris particle diameters seem small, their extremely high relative velocities in LEO (average 10 km/s) give them large kinetic energies. For instance, impact with a typical 3-mm particle in space is analogous to impact with a bowling ball at 60 miles per hour. Impact with a 1-cm particle has the same kinetic energy as impact with a 400-lb security safe at 60 miles per hour (Fig. 3). Thus it is obvious that the problem of tiny orbiting particles impacting a thin-film, inflatable solar concentrator is not trivial.

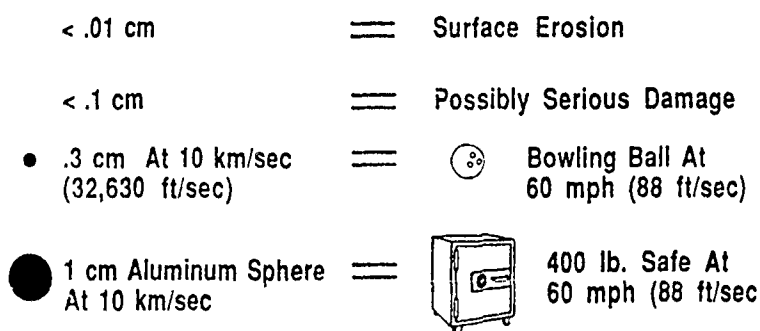


Figure 3. Kinetic Energy of Space Debris

Certain areas around the earth have higher orbital debris densities than others. Debris densities are highly dependent on altitude and inclination. Other orbital elements such as line of nodes and eccentricity are similar and average out (Ref. 5, p. 18).

Highest debris density occurs in the 2,000-km altitude band. Within this band distinct peaks occur at altitudes of 800 km and 1400 km (Fig. 4)(Ref. 6, p. 3-4). Notice that in Figure 5 the spatial densities of orbital debris drop off considerably from 1500 km to GEO.

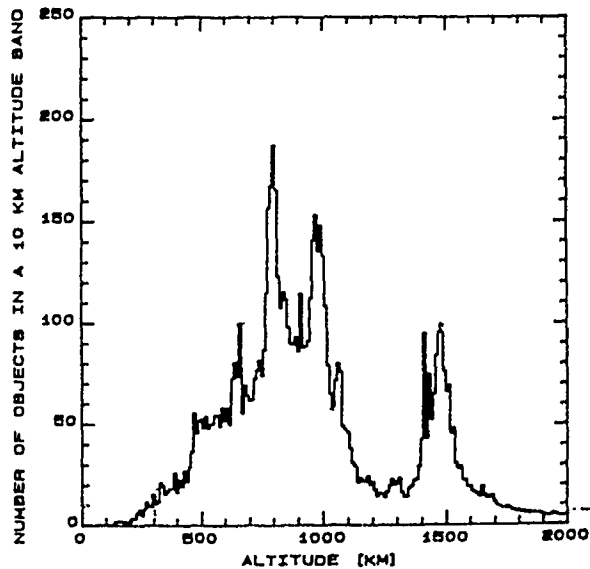


Figure 4. Altitude Distribution of Trackable Debris (Ref. 4, p. 4)

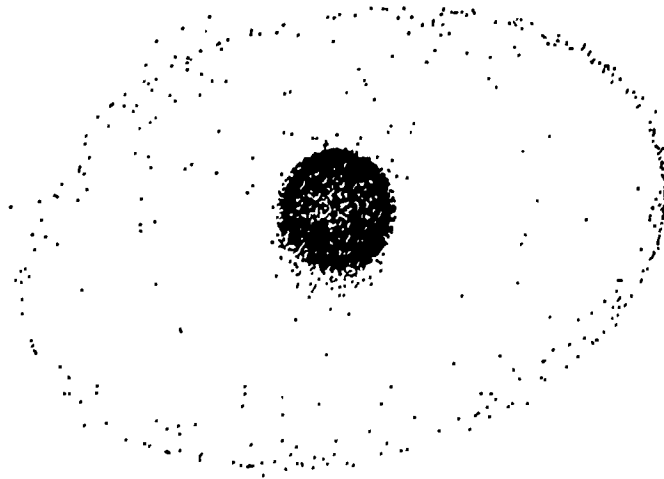


Figure 5. Overall Earth Orbit Distribution (Ref. 6, p. 12)

Debris densities are also greater at higher inclinations because space activity is more prevalent in these areas. As a space vehicle travels along its transfer orbit large amounts of

debris are left behind. Peak density inclinations are around 75 deg where there is a critical inclination (63 deg), 82 deg, sunsynchronous orbits (100 deg) and polar orbits (90 deg)(Ref. 5, p. 18).

Most debris particles are in very near circular orbits, with an eccentricity of less than 0.05. A natural circularization of debris orbits is a result of air drag on the particle (Ref. 5, p. 18).

Intentional satellite breakups and explosions are the largest source of debris. Because of the frequency of occurrence, intentional explosions of satellites is the largest source of debris and the practice must be discontinued immediately. "As a result (of an explosion) the fragments initially form an elliptical cloud of shrapnel. Over time the differential orbital parameters of the fragments cause the cloud to dissociate into a torus about the Earth." 1 (See Fig. 6.)

Collisions of two satellites or debris particles at hypervelocity impacts (average 10 km/s) could produce up to 10 times the amount of particles that an explosion creates. These collisions would also complicate the environment because the size of particles expelled is much smaller than that of average explosion particles. Other sources of debris particles are satellite deterioration and operational mission activities.

Current mathematical models consider various traffic patterns and satellite breakups to predict future debris populations. Some theorists feel that these models show that if current launch procedures continue at increased rates, debris collision will become much more prevalent because the population of small size debris could increase 10% per year.

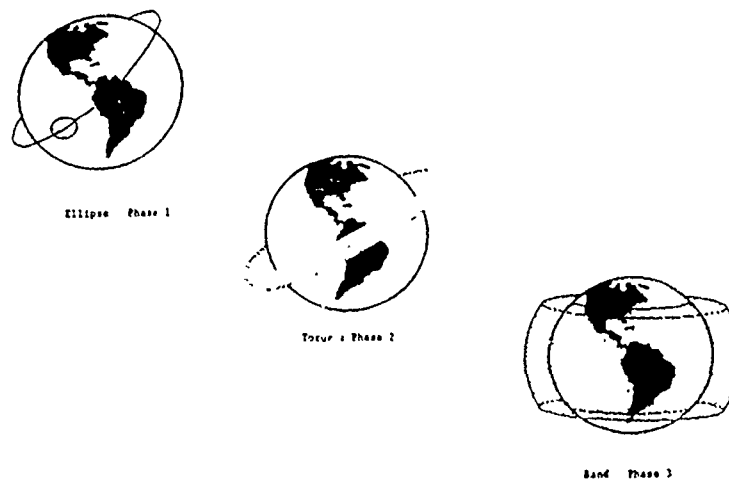


Figure 6. Phases of Debris Cloud Evolution (Ref. 3, p. 2)

A 10% per year increase rate could result in an unstable environment in which a critical particle density is reached and random debris collision approach runaway rates. We could reach this critical density as soon as the mid 21st century and an unstable environment not long after in the late 21st century (Ref. 2, p. 12).

According to Donald J. Kessler (NASA/JSC), "Based on today's launch rates and the natural population decay rate, extrapolated to the year 2000+, there may be a hazardous collision among any two space objects once every 1 to 4 years." (Ref. 5, p. 20)

Calculations modeling space debris flux and collision probabilities are very uncertain. Insufficient data on small particles, unknown levels of future space activities (launch rates), the randomness of our orbital debris cloud, and possible exaggerated debris growth rates.

CONCENTRATOR ISSUES

The effect of meteoroids and orbital debris on the balloon-like concentrators is a major question. To answer this question, we need to consider a number of parameters including: the transfer orbit profile and trip time, the projected area relative to the velocity vector, total time spent in an altitude interval, the material of the concentrator skin, the pressure and volume inside the concentrator, and the amount and size of holes in the concentrator.

The transfer orbit for the SPC is uncertain. Recently the Astronautics Laboratory has performed computer optimizations to determine the best transfer orbit profile. The driving factors were 1000 sec Isp, 50,000 lbm initial weight out of the shuttle bay at LEO, 50 lbf of estimated thrust, and 0.5 thruster efficiency.

Right now a multiple burn Hohman transfer is the most efficient and practical SPC transfer. The Fortran program called Multiburn was modified to help design a solar propulsion mission (Ref. 7). Multiburn performs a trajectory analysis for multiple burn

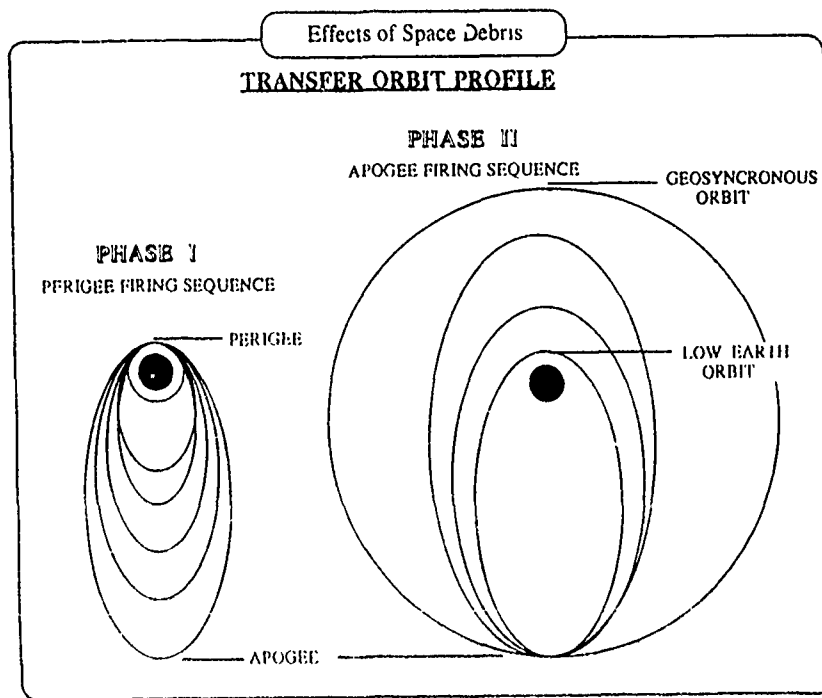


Figure 7. Solar Propulsion Transfer Strategy

transfers. Program results show that numerous perigee burns and a couple of apogee burns produce the best transfer profiles. Modified multiburn results are contained in Appendix A.

Figure 7 illustrates that the strategy of this transfer is to raise the radius of apogee with consecutive perigee burns until a geosynchronous altitude is reached. At this point the SPC is in an elliptical orbit with a perigee altitude of 280 km (approximate) and an apogee altitude of 35,800 km (GEO).

The second phase of the transfer is to raise the perigee altitude out to GEO by performing consecutive apogee burns. The final apogee firing would circularize the transfer at GEO.

Although the complete evaluation and optimization of the number of burns is not yet complete, a ratio of 10 perigee burns to every apogee burn seems a good first assumption. Table 3 shows the number of burns used as a rough approximation in this space debris scenario.

| Table 3. SPC Transfer Orbit Profile (Estimated) |
|--|
| Perigee burns = 120 |
| Apogee burns = 12 |
| Approximate trip time = 24.8 days |
| Projected reflector area = 100 m ² (each) |

The acronym HAIR stands for highly accurate inflatable reflectors. The HAIR is currently the most acceptable concentrator design for the solar propulsion concept. In the mid 1980's the basic concept was designed and developed using thin films to make the inflatable "clam shell" reflectors.

Inflatable concentrators are preferred over other types of rigid concentrators because of their large weight savings to GEO. The HAIR design would yield concentration ratios greater than 10,000:1 to assure that the minimum amount of energy is transferred to the fuel to expand the gas and propel the spacecraft.

In 1986 a firm called L'Garde presented their final report on their development of these inflatable reflectors for the SPC. Using their 1986 results and parameters for all calculations, L'Garde is furthering their design and development of these reflectors.

The material used for the reflective surface of the parabola will be 0.25-mm thick Teflon with vapor deposited aluminum. The internal pressure for inflation and reflectance is 2.46E-04 psi. L'Garde calculates the gas volume for the two collectors to be 175,000 cubic feet (Ref. 8, p. 10-15).

APPROACH TO THE DEFLATION PROBLEM

The focus of the deflation problem is determining the number and size of all the space debris particles that will penetrate the concentrators during a transfer and at what time the particles make the penetration.

Many assumptions had to be made in order to calculate the amount of inflatable lost during a typical SPC mission. These included:

1. Calculate the particle flux at worst case altitude (800 km) as a first cut approximation.
2. Assume a high density inclination.
3. Assume an average 0.5-mm orbital debris diameter for man-made hits based on probabilities.
4. Assume an average 0.2-mm meteoroid diameter for all meteoroid hits based on probabilities.
5. Assume that collisions with particles less than 0.1 mm will not penetrate the concentrators.
6. Assume the flow of helium through the holes is isentropic (frictionless), conservation of mass, and constant density.
7. Assume the particle only creates a hole in one side of the concentrator.
8. Assume that the length of the mission is 36 days or 1/10 of a year.
9. Assume that the area of the holes will be cumulative starting with day 1 and that the total loss of inflatable is exponential with time.
10. Assume that orbital debris growth will be roughly 10% per year.
11. Assume that the diameter of a hole in the concentrator is equal to the diameter of the particle that impacted. (This assumption should be acceptable because the other 10 assumptions are for a worst case scenario.)

To determine the amount of inflatable needed to replace inflatable lost due to space debris leaks requires an estimate of the number and size of particle hits. Flux graphs based on different mathematical models were analyzed to derive an impact rate. Read the flux graphs in Figures 8 and 9 carefully. The graphs are on a logarithmic scale and show impacts per time versus a particle size. The x axis shows a cumulative particle size. The y axis shows flux which is the number of impacts per year on a given surface area. In Figure 8 the flux of a 1-cm particle or greater is 0.4 impacts on a large space structure at an altitude of 500 km and an inclination of 30 degrees. That is approximately one impact every 2.5 years. This would be a catastrophic hit for most small satellites.

Figure 9 is the flux graph used in the Astronautics Laboratory's calculations because it is the worst case altitude and inclination. The spacecraft surface area will be scaled up to 2000 square meters by a factor of 50.

Consequently, the two concentrators can expect an impact with a 2-mm particle or greater (approximately) every year if they were continuously in that worst case orbit fully inflated.

Impact Rates on Large Space Structure
altitude = 500 km, inclination = 30 deg

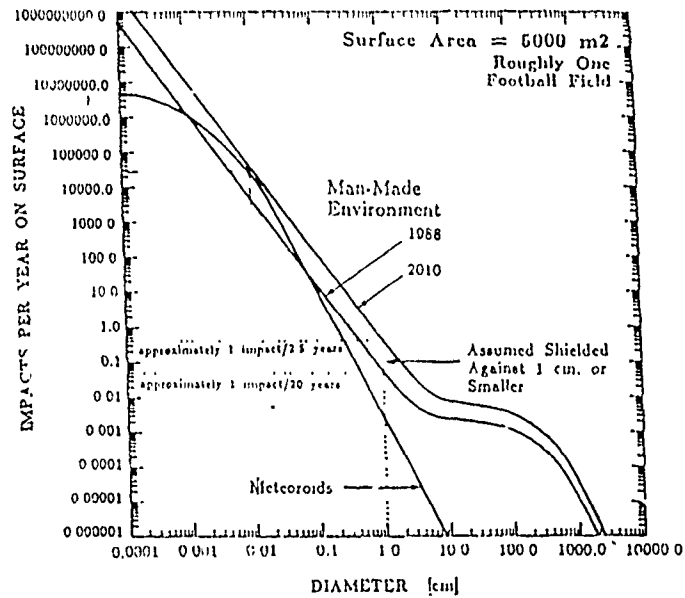


Figure 8. Space Debris Impacts on a Large Class Spacecraft (Ref. 4, p. 15)

Impact Rates on Average Small Satellite
altitude = 800 km; inclination = 80 deg

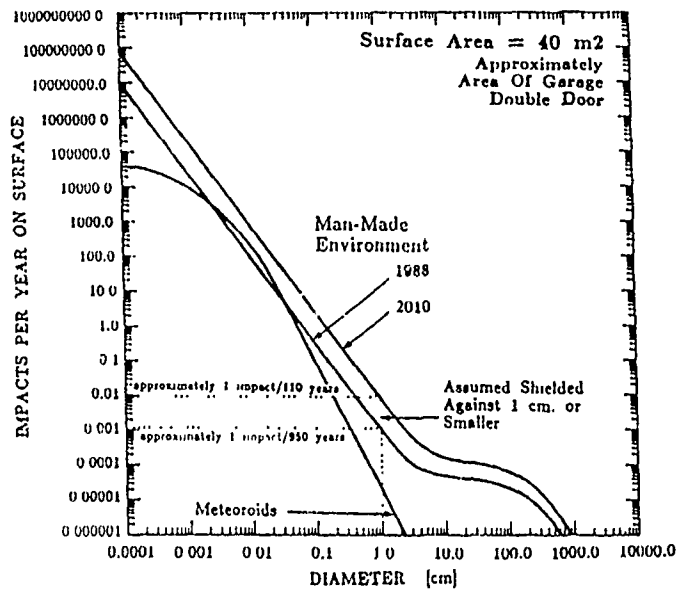


Figure 9. Space Debris Impacts on a Small Spacecraft (Ref. 4, p. 16)

To calculate an average mission flux consider the meteoroid and man-made debris separately. Figure 8 shows the meteoroid flux at the 0.01-cm (0.1-mm) mark to be 200 impacts per year. To scale up the reflectors' surface area multiply by a factor of 50. Then the flux works out to 10,000 hits per year.

There are two rates for man-made debris: the current rate and a predicted future date. The 1988 flux rate of 100 impacts per year, when scaled up by a factor of 50, becomes 5,000 impacts per year. Given a 10% annual increase in population, the predicted flux for the year 2010 is 900 impacts per year. Scaled up for a 2,000 square meter area, the rate becomes 45,000 impacts per year (Ref. 4, p. 15-16). Table 4 summarizes the impact rate calculations.

| Table 4. Impact Rates for Two (1000 m ²) Concentrations | | |
|---|-------------|--------------|
| Year | Debris Type | Impacts/Year |
| 1988 | Man-made | 5,000 |
| 2010 | Man-made | 45,000 |
| 1988 | Meteoroid | 10,000 |
| 2010 | Meteoroid | 10,000 |
| ** Impacts are for 0.1 mm and greater particles | | |

Next, using the previous impact rate calculation, we must calculate the area of the hole produced by an average size impact. Since our man-made and natural debris average diameters are 0.5 mm and 0.2 mm, respectively, the area for a single particle hit is assumed to be :

| | |
|---------------------------|------------------------------|
| Man-Made Particles 0.5 mm | 1.9635 x 10 ⁻³ cm |
| Natural Meteoroid 0.2 mm | 3.1416 x 10 ⁻⁴ cm |

The conservation of mass flow (i.e., in a rocket engine when the mass of the escaping gas equals the mass created by burning the fuel) and constant density were assumed. The following procedure was used to calculate the inflatant lost:

$$A_1 \cdot V_1 = A_2 \cdot V_2$$

For very small openings escape velocity of the inflatant is (Ref. 9, p. 239):

$$V_2 = [2(P_1 - P_2) / \text{Density}]^{1/2}$$

Calculate density of helium at 2.46E-04 psi and 277.8 Kelvin.

$$\text{Density} = 2.9304 \times 10^{-9} \text{ g/cm}^3$$

Calculate the gas's escape velocity:

$$V_2 = 1076 \text{ m/sec (Assume } P_2 = 0 \text{ psi)}$$

Calculate an inflatant loss rate: $A2 \cdot V2 \cdot \text{Density lbs} / (\text{day} \cdot \text{hit})$.

$$\text{Man-Made loss rate} = 1.1795 \times 10^{-4} \text{ lbs}/(\text{hit day})$$

$$\text{Natural loss rate} = 1.8872 \times 10^{-5} \text{ lbs}/(\text{hit day})$$

Calculate a Hit*Day factor for a 40-day mission:

- a) Divide the number of Hits/year by 365.
- b) Multiply that number by 40 days for a linear relationship.
- c) Calculate an area under the curve by multiplying b) by 40 days again and divide by 2.

$$\text{Man-Made} = (123 \cdot 40 \cdot 40/2) = 98,400 \text{ Hit} \cdot \text{Day}$$

$$\text{Natural} = (27.4 \cdot 40 \cdot 40/2) = 21,920 \text{ Hit} \cdot \text{Day}$$

To find the total amount of extra inflatant needed, multiply loss rate by Hit*Day factor to get lbs of gas required to keep reflectors inflated for 40 day mission. A summary of these results are in Table 5.

| Table 5. Inflatant Needed to Compensate for Debris Leaks | |
|--|---------------------|
| Man-made | 11.61 lbs |
| Natural | 0.41 lbs |
| Total | 12.02 lbs of helium |

Compared with the L'Garde results, 12.02 lbs of helium to compensate for debris leaks is much lower. The problem with this result is not the method of analysis but the assumption of an average particle size. A better approach would be to obtain a sample. Base distribution on the probabilities of particle impact, simulate hits for a variety of particle sizes, and calculate the losses as time goes on.

Performing this type of calculation becomes very time consuming. It would be much easier for a computer program to perform the calculations. Future modifications to the Multiburn program will incorporate this approach and yield more accurate numbers.

The real value of this investigation into the inflation problem is the discovery of its vast complexities. Further research is needed to see if a inflatable concentrator is truly realistic.

Remaining Issues

The problem with calculating impacts on a reflector which is in an elliptical transfer orbit has not yet been addressed. The calculations were performed assuming a circular orbit at a constant altitude. A relatively short computer program could integrate these changing parameters for noncircular orbits and then calculate particle impacts and deflation rates.

Also the position of the concentrators into low profiles or low projected areas with respect to the direction of flight can result in a significantly smaller number of hits.

Although the amount of inflatant turned out to be relatively low, the errors and assumptions identified the fact that different dependent and independent variables need to be considered. Further development of computer calculations for elliptical transfer orbits and development of the impact calculation for various sized particles will result in a more accurate inflatant weight determination.

CATASTROPHIC COLLISION PROBABILITY

Calculating the probability of a catastrophic impact with a piece of trackable debris is important in determining the feasibility of the system. Because the concentrators have such a large surface area, the risk of collision is greater than it is for an average satellite mission.

One possible approach for this calculation makes use of the kinetic theory of gases. The modified Multiburn program performs many iterations to calculate the total amount of time the spacecraft spends in an altitude interval after several elliptical transfer orbits. (See Appendix B.) Applying the kinetic theory of gases, Multiburn calculates probabilities using the total amount of time spent in a certain spatial density.

Applying this theory to a typical solar propulsion mission, the probability of collision with a piece of orbital debris in low earth orbit can be calculated. This probability is a function of: 1) relative velocity between the spacecraft and orbital debris; 2) the projected cross sectional area of the spacecraft; 3) spatial density of debris traveled through and 4) the time spent passing through that volume. Figure 10 below illustrates the probability of collision (Ref. 3, p. 3).

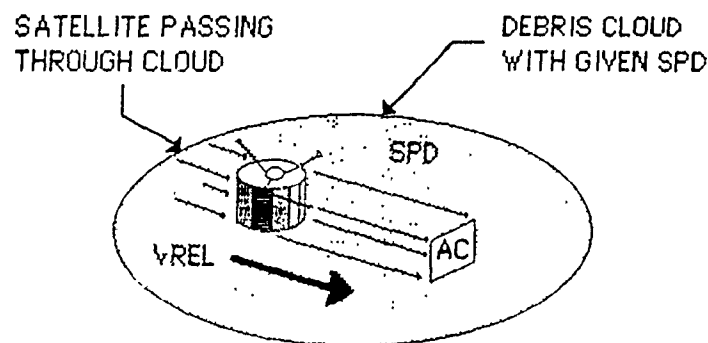


Figure 10. Probability of Collision

Spatial density (SPD) is a mean population density as a function of altitude and the amount of debris in a given volume band. The SPD term is calculated by finding the average number of objects located within 50 km wide concentric volume shells.

The probability equation from Reference 10, p. 3 is:

$$PC = 1 - \exp [-(SPD * AC * Vrel * TOP)]$$

** if PC is small, then $PC = (SPD * AC * Vrel * TOP)$

PC = probability of collision

AC = cross-sectional area of spacecraft (km²)
 SPD = number of objects per cubic km
 Vrel = relative velocity between satellite and debris
 TOP = time of passage (sec)

A first attempt at analyzing the SPC transfer orbit used time intervals (TOP) of one year in each altitude band. Since the space shuttle is to deliver the SPC at approximately 280 km, the first probability uses the highest spatial density in a 200-km altitude interval starting at an altitude of 200 km. The last probability is at 2400 km because the spatial density becomes so small that the probability of collision is negligible. Table 6 lists the catastrophic collision probabilities.

The problem with using one year time intervals is that a SPC mission is only 40 days. Also as previously mentioned the series of perigee and apogee burns are elliptical transfer orbits that are constantly changing in altitude over time. The modified Multiburn computer program adds up the total time spent in each 200-km altitude band. Results of these total times at an altitude interval are contained in Appendix B. Results reveal that the longest time spent in a single altitude band (200-400 km) is about one day (assuming 120 perigee burns and 12 apogee burns). Table 6 also shows the probabilities of collision for one day at each interval.

The other data used in the probability calculation is:

$$V_{rel} = 10 \text{ km/sec}$$

$$AC = 2,000 \text{ m}^2$$

$$SPD = \text{See Appendix C (Ref. 10)}$$

| Table 6. Catastrophic Collision Probabilities | | | |
|---|------------------------------------|--------------------|-------------------|
| Altitude (km) | SPD (No. objects/km ²) | 1 year Probability | 1 day Probability |
| 200-400 | 0.16051E-08 | 0.001 | 0.000003 |
| 400-600 | 0.56945E-08 | 0.030 | 0.000082 |
| 600-800 | 0.13564E-07 | 0.086 | 0.00023 |
| 800-1000 | 0.15585E-07 | 0.098 | 0.00077 |
| 1000-1200 | 0.89068E-08 | 0.056 | 0.00015 |
| 1200-1400 | 0.24093E-08 | 0.015 | 0.000042 |
| 1400-1600 | 0.95707E-08 | 0.060 | 0.00017 |
| 1600-1800 | 0.25119E-08 | 0.016 | 0.000043 |
| 1800-2000 | 0.74911E-09 | 0.0047 | 0.000013 |
| 2000-2200 | 0.51456E-09 | 0.0033 | 0.000009 |
| 2200-2400 | 0.21176E-09 | 0.0013 | 0.000004 |

The results from Table 6 clearly show that for a 30-40 day transfer orbit, the chance of colliding with a piece of trackable debris is 0.1 percent at the highest density altitude (800

km). As an unrealistic overestimation of one orbiting at 800 km give us 9.8 percent chance of catastrophic collision. Even though these probabilities are very small, the approach and the computer code will be beneficial in the future as the space debris population grows.

Debris Contour Maps

An interesting idea developed during this research program was artificial debris contour plots for future orbit and mission designers. These maps take existing data such as altitude/population distributions and inclination/population distributions and combine them into one color coded contour plot. These maps would show high risk areas as a function of altitude and inclination. High risk contour plots of debris would allow astronautical engineers and orbit designers to avoid high density areas if possible. Sample plots are contained in Appendix D. The data to generate these plots was limited and the program was not able to extrapolate to get even contours but the idea could be useful in the future.

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APPENDIX A

MULTIBURN TRANSFER ORBIT RESULTS

PERIGEE BURNS

| BURN NUMBER | MASS RATIO | DELV BURN | DELV TOT | THIS TIME | TOTAL TIME | PROP BURN |
|----------------|------------|-----------|----------|-----------|------------|-----------|
| 1 | .9980289 | 67.08 | 67.08 | 1.5124 | 1.5124 | 98.557 |
| 2 | .9980288 | 67.08 | 134.16 | 1.5238 | 3.0362 | 98.367 |
| 3 | .9980287 | 67.09 | 201.25 | 1.5354 | 4.5715 | 98.179 |
| 4 | .9980285 | 67.09 | 268.34 | 1.5471 | 6.1186 | 97.993 |
| 5 | .9980283 | 67.10 | 335.44 | 1.5591 | 7.6777 | 97.810 |
| 6 | .9980280 | 67.11 | 402.55 | 1.5712 | 9.2489 | 97.630 |
| 7 | .9980277 | 67.12 | 469.67 | 1.5835 | 10.8324 | 97.453 |
| 8 | .9980274 | 67.13 | 536.80 | 1.5960 | 12.4284 | 97.278 |
| 9 | .9980270 | 67.14 | 603.94 | 1.6087 | 14.0371 | 97.106 |
| 10 | .9980265 | 67.16 | 671.10 | 1.6216 | 15.6587 | 96.936 |
| 11 | .9980260 | 67.18 | 738.28 | 1.6347 | 17.2934 | 96.769 |
| 12 | .9980255 | 67.19 | 805.47 | 1.6481 | 18.9415 | 96.605 |
| 13 | .9980249 | 67.21 | 872.69 | 1.6616 | 20.6031 | 96.443 |
| 14 | .9980243 | 67.24 | 939.92 | 1.6754 | 22.2785 | 96.283 |
| 15 | .9980236 | 67.26 | 1007.18 | 1.6894 | 23.9680 | 96.126 |
| 16 | .9980228 | 67.28 | 1074.47 | 1.7037 | 25.6716 | 95.972 |
| 17 | .9980221 | 67.31 | 1141.78 | 1.7181 | 27.3898 | 95.820 |
| 18 | .9980212 | 67.34 | 1209.12 | 1.7329 | 29.1226 | 95.670 |
| 19 | .9980204 | 67.37 | 1276.48 | 1.7479 | 30.8705 | 95.523 |
| 20 | .9980195 | 67.40 | 1343.88 | 1.7631 | 32.6336 | 95.378 |
| 21 | .9980185 | 67.43 | 1411.32 | 1.7786 | 34.4122 | 95.235 |
| 22 | .9980175 | 67.47 | 1478.78 | 1.7944 | 36.2067 | 95.095 |
| 23 | .9980164 | 67.50 | 1546.29 | 1.8105 | 38.0172 | 94.957 |
| 24 | .9980153 | 67.54 | 1613.83 | 1.8269 | 39.8440 | 94.822 |
| 25 | .9980142 | 67.58 | 1681.41 | 1.8435 | 41.6875 | 94.689 |
| 26 | .9980130 | 67.62 | 1749.03 | 1.8605 | 43.5480 | 94.558 |
| 27 | .9980117 | 67.66 | 1816.70 | 1.8778 | 45.4258 | 94.429 |
| 28 | .9980104 | 67.71 | 1884.40 | 1.8954 | 47.3211 | 94.303 |
| 29 | .9980091 | 67.75 | 1952.16 | 1.9133 | 49.2344 | 94.179 |
| 30 | .9980077 | 67.80 | 2019.96 | 1.9316 | 51.1660 | 94.057 |
| 31 | .9980062 | 67.85 | 2087.81 | 1.9502 | 53.1162 | 93.937 |
| 32 | .9980048 | 67.90 | 2155.71 | 1.9692 | 55.0853 | 93.820 |
| 33 | .9980032 | 67.95 | 2223.66 | 1.9885 | 57.0739 | 93.704 |
| 34 | .9980017 | 68.01 | 2291.67 | 2.0083 | 59.0821 | 93.591 |
| 35 | .9980000 | 68.06 | 2359.73 | 2.0284 | 61.1105 | 93.480 |
| 36 | .9979984 | 68.12 | 2427.85 | 2.0489 | 63.1594 | 93.371 |
| 37 | .9979966 | 68.18 | 2496.03 | 2.0698 | 65.2292 | 93.264 |
| 38 | .9979949 | 68.24 | 2564.26 | 2.0912 | 67.3205 | 93.159 |
| 39 | .9979931 | 68.30 | 2632.56 | 2.1130 | 69.4335 | 93.057 |
| 40 | .9979912 | 68.36 | 2700.92 | 2.1353 | 71.5688 | 92.956 |
| 41 | .9979893 | 68.43 | 2769.35 | 2.1580 | 73.7268 | 92.857 |
| 42 | .9979873 | 68.49 | 2837.85 | 2.1812 | 75.9081 | 92.761 |
| 43 | .9979853 | 68.56 | 2906.41 | 2.2050 | 78.1130 | 92.666 |
| 44 | .9979833 | 68.63 | 2975.04 | 2.2292 | 80.3422 | 92.573 |
| 45 | .9979812 | 68.70 | 3043.74 | 2.2539 | 82.5962 | 92.483 |
| 46 | .9979790 | 68.78 | 3112.52 | 2.2793 | 84.8754 | 92.394 |
| 47 | .9979769 | 68.85 | 3181.37 | 2.3051 | 87.1805 | 92.307 |
| 48 | .9979746 | 68.93 | 3250.30 | 2.3316 | 89.5121 | 92.222 |
| 49 | .9979723 | 69.01 | 3319.30 | 2.3586 | 91.8708 | 92.139 |
| 50 | .9979700 | 69.08 | 3388.39 | 2.3863 | 94.2571 | 92.058 |
| 51 | .9979676 | 69.17 | 3457.55 | 2.4146 | 96.6717 | 91.979 |
| 52 | .9979652 | 69.25 | 3526.80 | 2.4436 | 99.1153 | 91.902 |
| 53 | .9979627 | 69.33 | 3596.14 | 2.4733 | 101.5886 | 91.826 |
| 54 | .9979602 | 69.42 | 3665.55 | 2.5037 | 104.0923 | 91.752 |
| 55 | .9979576 | 69.51 | 3735.06 | 2.5348 | 106.6271 | 91.680 |
| 56 | .9979550 | 69.59 | 3804.65 | 2.5667 | 109.1938 | 91.610 |
| 57 | .9979524 | 69.69 | 3874.34 | 2.5994 | 111.7932 | 91.542 |

| | | | | | | |
|-----|----------|-------|---------|---------|----------|--------|
| 58 | .9979497 | 69.78 | 3944.12 | 2.6329 | 114.4261 | 91.475 |
| 59 | .9979469 | 69.87 | 4013.99 | 2.6672 | 117.0934 | 91.410 |
| 60 | .9979441 | 69.97 | 4083.96 | 2.7025 | 119.7958 | 91.347 |
| 61 | .9979413 | 70.06 | 4154.02 | 2.7386 | 122.5345 | 91.286 |
| 62 | .9979384 | 70.16 | 4224.18 | 2.7757 | 125.3102 | 91.226 |
| 63 | .9979354 | 70.26 | 4294.45 | 2.8138 | 128.1240 | 91.168 |
| 64 | .9979324 | 70.36 | 4364.81 | 2.8529 | 130.9770 | 91.111 |
| 65 | .9979294 | 70.47 | 4435.28 | 2.8931 | 133.8701 | 91.057 |
| 66 | .9979263 | 70.57 | 4505.85 | 2.9344 | 136.8045 | 91.003 |
| 67 | .9979232 | 70.68 | 4576.53 | 2.9768 | 139.7813 | 90.952 |
| 68 | .9979200 | 70.79 | 4647.32 | 3.0205 | 142.8018 | 90.902 |
| 69 | .9979168 | 70.90 | 4718.22 | 3.0654 | 145.8672 | 90.853 |
| 70 | .9979135 | 71.01 | 4789.23 | 3.1115 | 148.9787 | 90.807 |
| 71 | .9979102 | 71.12 | 4860.35 | 3.1591 | 152.1378 | 90.761 |
| 72 | .9979068 | 71.24 | 4931.59 | 3.2080 | 155.3458 | 90.718 |
| 73 | .9979034 | 71.35 | 5002.94 | 3.2585 | 158.6043 | 90.675 |
| 74 | .9978999 | 71.47 | 5074.41 | 3.3104 | 161.9147 | 90.635 |
| 75 | .9978964 | 71.59 | 5146.01 | 3.3640 | 165.2787 | 90.595 |
| 76 | .9978929 | 71.71 | 5217.72 | 3.4193 | 168.6980 | 90.558 |
| 77 | .9978893 | 71.84 | 5289.55 | 3.4763 | 172.1742 | 90.521 |
| 78 | .9978856 | 71.96 | 5361.51 | 3.5351 | 175.7093 | 90.486 |
| 79 | .9978819 | 72.09 | 5433.60 | 3.5959 | 179.3052 | 90.453 |
| 80 | .9978782 | 72.21 | 5505.81 | 3.6587 | 182.9639 | 90.421 |
| 81 | .9978744 | 72.34 | 5578.15 | 3.7236 | 186.6874 | 90.390 |
| 82 | .9978705 | 72.47 | 5650.63 | 3.7907 | 190.4781 | 90.361 |
| 83 | .9978667 | 72.61 | 5723.23 | 3.8601 | 194.3382 | 90.333 |
| 84 | .9978627 | 72.74 | 5795.97 | 3.9320 | 198.2702 | 90.306 |
| 85 | .9978588 | 72.87 | 5868.85 | 4.0064 | 202.2766 | 90.281 |
| 86 | .9978547 | 73.01 | 5941.86 | 4.0836 | 206.3601 | 90.257 |
| 87 | .9978507 | 73.15 | 6015.01 | 4.1635 | 210.5237 | 90.235 |
| 88 | .9978465 | 73.29 | 6088.30 | 4.2465 | 214.7702 | 90.213 |
| 89 | .9978424 | 73.43 | 6161.73 | 4.3326 | 219.1028 | 90.193 |
| 90 | .9978381 | 73.58 | 6235.31 | 4.4221 | 223.5249 | 90.174 |
| 91 | .9978339 | 73.72 | 6309.03 | 4.5151 | 228.0400 | 90.157 |
| 92 | .9978296 | 73.87 | 6382.90 | 4.6118 | 232.6518 | 90.141 |
| 93 | .9978252 | 74.02 | 6456.92 | 4.7124 | 237.3642 | 90.125 |
| 94 | .9978208 | 74.17 | 6531.09 | 4.8172 | 242.1814 | 90.111 |
| 95 | .9978164 | 74.32 | 6605.40 | 4.9264 | 247.1078 | 90.099 |
| 96 | .9978119 | 74.47 | 6679.88 | 5.0403 | 252.1481 | 90.087 |
| 97 | .9978073 | 74.63 | 6754.50 | 5.1591 | 257.3072 | 90.077 |
| 98 | .9978027 | 74.78 | 6829.29 | 5.2833 | 262.5905 | 90.067 |
| 99 | .9977981 | 74.94 | 6904.23 | 5.4131 | 268.0036 | 90.059 |
| 100 | .9977934 | 75.10 | 6979.33 | 5.5489 | 273.5525 | 90.052 |
| 101 | .9977887 | 75.26 | 7054.59 | 5.6911 | 279.2435 | 90.046 |
| 102 | .9977839 | 75.43 | 7130.02 | 5.8401 | 285.0836 | 90.041 |
| 103 | .9977791 | 75.59 | 7205.61 | 5.9964 | 291.0800 | 90.037 |
| 104 | .9977742 | 75.76 | 7281.36 | 6.1606 | 297.2407 | 90.034 |
| 105 | .9977693 | 75.92 | 7357.28 | 6.3332 | 303.5739 | 90.033 |
| 106 | .9977643 | 76.09 | 7433.38 | 6.5149 | 310.0887 | 90.032 |
| 107 | .9977593 | 76.26 | 7509.64 | 6.7062 | 316.7949 | 90.032 |
| 108 | .9977542 | 76.44 | 7586.08 | 6.9080 | 323.7030 | 90.033 |
| 109 | .9977491 | 76.61 | 7662.69 | 7.1212 | 330.8242 | 90.035 |
| 110 | .9977440 | 76.79 | 7739.47 | 7.3466 | 338.1707 | 90.038 |
| 111 | .9977388 | 76.96 | 7816.43 | 7.5852 | 345.7559 | 90.042 |
| 112 | .9977335 | 77.14 | 7893.58 | 7.8382 | 353.5941 | 90.047 |
| 113 | .9977282 | 77.32 | 7970.90 | 8.1068 | 361.7008 | 90.053 |
| 114 | .9977229 | 77.50 | 8048.40 | 8.3925 | 370.0933 | 90.060 |
| 115 | .9977175 | 77.69 | 8126.09 | 8.6967 | 378.7901 | 90.068 |
| 116 | .9977121 | 77.87 | 8203.96 | 9.0214 | 387.8115 | 90.076 |
| 117 | .9977066 | 78.06 | 8282.02 | 9.3684 | 397.1799 | 90.086 |
| 118 | .9977010 | 78.25 | 8360.27 | 9.7400 | 406.9199 | 90.096 |
| 119 | .9976955 | 78.44 | 8438.71 | 10.1388 | 417.0587 | 90.107 |
| 120 | .9976898 | 78.63 | 8517.34 | 5.2838 | 422.3425 | 90.119 |

APOGEE BURNS

| BURN NUMBER | MASS RATIO | DELV BURN | DELV TOT | THIS TIME | TOTAL TIME | PROP BURN |
|----------------|------------|-----------|----------|-----------|------------|-----------|
| 1 | .9856745 | 475.63 | 475.63 | 11.0119 | 11.0119 | 557.541 |
| 2 | .9856343 | 476.97 | 952.60 | 11.5169 | 22.5288 | 551.096 |
| 3 | .9855673 | 479.21 | 1431.82 | 12.0914 | 34.6202 | 545.712 |
| 4 | .9854735 | 482.35 | 1914.17 | 12.7467 | 47.3669 | 541.330 |
| 5 | .9853530 | 486.38 | 2400.55 | 13.4971 | 60.8640 | 537.893 |
| 6 | .9852057 | 491.31 | 2891.86 | 14.3608 | 75.2247 | 535.345 |
| 7 | .9850316 | 497.13 | 3388.99 | 15.3616 | 90.5863 | 533.630 |
| 8 | .9848308 | 503.85 | 3892.85 | 16.5308 | 107.1171 | 532.694 |
| 9 | .9846033 | 511.47 | 4404.32 | 17.9100 | 125.0271 | 532.482 |
| 10 | .9843491 | 519.98 | 4924.30 | 19.5561 | 144.5832 | 532.940 |
| 11 | .9840682 | 529.39 | 5453.69 | 21.5482 | 166.1314 | 534.015 |
| 12 | .9837606 | 539.70 | 5993.39 | .0000 | 166.1314 | 535.653 |

***** MULTIBURN OUTPUT SUMMARY *****

***** ROCKET MASS SUMMARY *****

GROSS IGNITION WEIGHT (LBM) = 50000.00
 DRY MASS DELIVERED GEO (LBM) = 31849.34
 PROPELLANT MASS BURNED (LBM) = 18332.17
 VEHICLE INERT WEIGHT (LBM) = 3257.78
 DELIVERED PAYLOAD (LBM) = 28410.04
 WTHRST = 474.1
 WREF SYS = 598.8
 WFEEED = 1760.

***** ROCKET PERF SUMMARY *****

PROPELLANT MASS FRACTION = .849106
 ROCKET VACUUM THRUST (LBF) = 50.79
 SPECIFIC IMPULSE (SEC) = 1000.000
 MAXIMUM ACCELERATION (G) = .001595
 MINIMUM ACCELERATION (G) = .001016
 NUMBER OF PERIGEE BURNS = 120
 NUMBER OF APOGEE BURNS = 12
 RNORM = 15.90
 POWIN = 2.2156E+06

***** ORBITAL INFORMATION *****

INITIAL ORBIT

INITIAL ORBITAL ALT (NMI) = 150.00
 INITIAL ORBIT RADIUS (NMI) = 3593.92
 INITIAL ORBIT PERIOD (HRS) = 1.5011
 INITIAL ORBIT VELOCITY (FPS) = 25389.23

TRANSFER ORBIT

ORBITAL PERIOD (HRS) = 10.5676
 PERIGEE VELOCITY (FPS) = 33372.62
 APOGEE VELOCITY (FPS) = 5258.63

FINAL ORBIT

APPENDIX B

MODIFIED MULTIBURN RESULTS

TOTAL TIMES SPENT AT A GIVEN ALTITUDE INTERVAL

```

1 ***** FINAL ALTITUDE AND TIME DATA
2 ALTITUDE INTERVAL (KM) AND TIME AT THAT INTERVAL (MINUTES)
3 200 TO 400 TIME (MINS) : 1542.
4 400 TO 600 TIME (MINS) : 1024.
5 600 TO 800 TIME (MINS) : 735.9
6 800 TO 1000 TIME (MINS) : 628.1
7 1000 TO 1200 TIME (MINS) : 474.0
8 1200 TO 1400 TIME (MINS) : 495.2
9 1400 TO 1600 TIME (MINS) : 433.6
10 1600 TO 1800 TIME (MINS) : 392.6
11 1800 TO 2000 TIME (MINS) : 405.3
12 2000 TO 2200 TIME (MINS) : 335.5
13 2200 TO 2400 TIME (MINS) : 327.3
14 2400 TO 2600 TIME (MINS) : 352.5
15 2600 TO 2800 TIME (MINS) : 327.6
16 2800 TO 3000 TIME (MINS) : 282.0
17 3000 TO 3200 TIME (MINS) : 277.5
18 3200 TO 3400 TIME (MINS) : 297.6
19 3400 TO 3600 TIME (MINS) : 275.7
20 3600 TO 3800 TIME (MINS) : 322.7
21 3800 TO 4000 TIME (MINS) : 245.7
22 4000 TO 4200 TIME (MINS) : 223.7
23 4200 TO 4400 TIME (MINS) : 252.1
24 4400 TO 4600 TIME (MINS) : 241.8
25 4600 TO 4800 TIME (MINS) : 241.9
26 4800 TO 5000 TIME (MINS) : 260.0
27 5000 TO 5200 TIME (MINS) : 251.1
28 5200 TO 5400 TIME (MINS) : 178.7
29 5400 TO 5600 TIME (MINS) : 221.5
30 5600 TO 5800 TIME (MINS) : 220.0
31 5800 TO 6000 TIME (MINS) : 225.4
32 6000 TO 6200 TIME (MINS) : 213.7
33 6200 TO 6400 TIME (MINS) : 183.6
34 6400 TO 6600 TIME (MINS) : 241.8
35 6600 TO 6800 TIME (MINS) : 222.6
36 6800 TO 7000 TIME (MINS) : 181.0
37 7000 TO 7200 TIME (MINS) : 199.9
38 7200 TO 7400 TIME (MINS) : 166.6
39 7400 TO 7600 TIME (MINS) : 195.4
40 7600 TO 7800 TIME (MINS) : 221.5
41 7800 TO 8000 TIME (MINS) : 152.3
42 8000 TO 8200 TIME (MINS) : 198.2
43 8200 TO 8400 TIME (MINS) : 164.9
44 8400 TO 8600 TIME (MINS) : 173.3
45 8600 TO 8800 TIME (MINS) : 187.4
46 8800 TO 9000 TIME (MINS) : 211.5
47 9000 TO 9200 TIME (MINS) : 193.6
48 9200 TO 9400 TIME (MINS) : 159.0
49 9400 TO 9600 TIME (MINS) : 163.9
50 9600 TO 9800 TIME (MINS) : 160.4
51 9800 TO 10000 TIME (MINS) : 116.6
52
53 10000 TO 10200 TIME (MINS) : 173.4
54 10200 TO 10400 TIME (MINS) : 160.9
55 10400 TO 10600 TIME (MINS) : 164.9
56 10600 TO 10800 TIME (MINS) : 186.0
57 10800 TO 11000 TIME (MINS) : 150.0
58 11000 TO 11200 TIME (MINS) : 195.1
59 11200 TO 11400 TIME (MINS) : 182.0
60 11400 TO 11600 TIME (MINS) : 187.5
61 11600 TO 11800 TIME (MINS) : 131.7
62 11800 TO 12000 TIME (MINS) : 122.9
63 12000 TO 12200 TIME (MINS) : 191.5
64 12200 TO 12400 TIME (MINS) : 138.8
65 12400 TO 12600 TIME (MINS) : 110.5

```

| | | | | | |
|-----|-------|----|-------|---------------|-------|
| 66 | 12600 | TO | 12800 | TIME (MINS) : | 116.9 |
| 67 | 12800 | TO | 13000 | TIME (MINS) : | 146.8 |
| 68 | 13000 | TO | 13200 | TIME (MINS) : | 155.7 |
| 69 | 13200 | TO | 13400 | TIME (MINS) : | 111.3 |
| 70 | 13400 | TO | 13600 | TIME (MINS) : | 206.4 |
| 71 | 13600 | TO | 13800 | TIME (MINS) : | 132.0 |
| 72 | 13800 | TO | 14000 | TIME (MINS) : | 125.8 |
| 73 | 14000 | TO | 14200 | TIME (MINS) : | 190.0 |
| 74 | 14200 | TO | 14400 | TIME (MINS) : | 178.2 |
| 75 | 14400 | TO | 14600 | TIME (MINS) : | 125.4 |
| 76 | 14600 | TO | 14800 | TIME (MINS) : | 134.8 |
| 77 | 14800 | TO | 15000 | TIME (MINS) : | 181.1 |
| 78 | 15000 | TO | 15200 | TIME (MINS) : | 141.9 |
| 79 | 15200 | TO | 15400 | TIME (MINS) : | 56.90 |
| 80 | 15400 | TO | 15600 | TIME (MINS) : | 199.8 |
| 81 | 15600 | TO | 15800 | TIME (MINS) : | 106.1 |
| 82 | 15800 | TO | 16000 | TIME (MINS) : | 194.9 |
| 83 | 16000 | TO | 16200 | TIME (MINS) : | 30.34 |
| 84 | 16200 | TO | 16400 | TIME (MINS) : | 221.7 |
| 85 | 16400 | TO | 16600 | TIME (MINS) : | 45.06 |
| 86 | 16600 | TO | 16800 | TIME (MINS) : | 91.85 |
| 87 | 16800 | TO | 17000 | TIME (MINS) : | 147.7 |
| 88 | 17000 | TO | 17200 | TIME (MINS) : | 124.8 |
| 89 | 17200 | TO | 17400 | TIME (MINS) : | 164.5 |
| 90 | 17400 | TO | 17600 | TIME (MINS) : | 172.7 |
| 91 | 17600 | TO | 17800 | TIME (MINS) : | 125.7 |
| 92 | 17800 | TO | 18000 | TIME (MINS) : | 80.86 |
| 93 | 18000 | TO | 18200 | TIME (MINS) : | 125.1 |
| 94 | 18200 | TO | 18400 | TIME (MINS) : | 215.4 |
| 95 | 18400 | TO | 18600 | TIME (MINS) : | 84.92 |
| 96 | 18600 | TO | 18800 | TIME (MINS) : | 267.3 |
| 97 | 18800 | TO | 19000 | TIME (MINS) : | 54.87 |
| 98 | 19000 | TO | 19200 | TIME (MINS) : | 55.55 |
| 99 | 19200 | TO | 19400 | TIME (MINS) : | 175.0 |
| 100 | 19400 | TO | 19600 | TIME (MINS) : | 56.91 |
| 101 | 19600 | TO | 19800 | TIME (MINS) : | 118.5 |
| 102 | 19800 | TO | 20000 | TIME (MINS) : | 197.3 |
| 103 | 20000 | TO | 20200 | TIME (MINS) : | 36.35 |
| 104 | 20200 | TO | 20400 | TIME (MINS) : | 103.7 |
| 105 | 20400 | TO | 20600 | TIME (MINS) : | 194.6 |
| 106 | 20600 | TO | 20800 | TIME (MINS) : | .0000 |
| 107 | 20800 | TO | 21000 | TIME (MINS) : | 165.4 |
| 108 | 21000 | TO | 21200 | TIME (MINS) : | 197.2 |
| 109 | 21200 | TO | 21400 | TIME (MINS) : | 80.52 |
| 110 | 21400 | TO | 21600 | TIME (MINS) : | 170.6 |
| 111 | 21600 | TO | 21800 | TIME (MINS) : | 162.2 |
| 112 | 21800 | TO | 22000 | TIME (MINS) : | 54.24 |
| 113 | 22000 | TO | 22200 | TIME (MINS) : | 177.5 |
| 114 | 22200 | TO | 22400 | TIME (MINS) : | 104.7 |
| 115 | 22400 | TO | 22600 | TIME (MINS) : | 43.01 |
| 116 | 22600 | TO | 22800 | TIME (MINS) : | 233.2 |
| 117 | 22800 | TO | 23000 | TIME (MINS) : | 98.20 |
| 118 | 23000 | TO | 23200 | TIME (MINS) : | 109.4 |
| 119 | 23200 | TO | 23400 | TIME (MINS) : | 74.89 |
| 120 | 23400 | TO | 23600 | TIME (MINS) : | 118.9 |
| 121 | 23600 | TO | 23800 | TIME (MINS) : | 180.2 |
| 122 | 23800 | TO | 24000 | TIME (MINS) : | 105.6 |
| 123 | 24000 | TO | 24200 | TIME (MINS) : | 156.4 |
| 124 | 24200 | TO | 24400 | TIME (MINS) : | .0000 |
| 125 | 24400 | TO | 24600 | TIME (MINS) : | 166.8 |
| 126 | 24600 | TO | 24800 | TIME (MINS) : | 33.94 |
| 127 | 24800 | TO | 25000 | TIME (MINS) : | 134.8 |
| 128 | 25000 | TO | 25200 | TIME (MINS) : | 126.1 |
| 129 | 25200 | TO | 25400 | TIME (MINS) : | 173.1 |
| 130 | 25400 | TO | 25600 | TIME (MINS) : | 171.3 |

APPENDIX C

SPATIAL DENSITIES

(Dr. D.S. Mc Knight)

Debris Samplings for Satellites

| Band (km) | No. Objects | Obj hr/day | Spatial Density (obj/cu km) |
|--------------|-------------|------------|-----------------------------|
| 0 to 50 | 1 | 1.606929 | 0.2599062456941053E-11 |
| 50 to 100 | 4 | 3.126543 | 0.4978840550166816E-11 |
| 100 to 150 | 19 | 8.267196 | 0.1296337336934861E-10 |
| 150 to 200 | 65 | 147.6135 | 0.2279467036104500E-09 |
| 200 to 250 | 138 | 174.9145 | 0.2660302029101430E-09 |
| 250 to 300 | 252 | 411.5040 | 0.6164911281471052E-09 |
| 300 to 350 | 344 | 1087.587 | 0.1605142005971773E-08 |
| 350 to 400 | 428 | 1065.965 | 0.1550021681088194E-08 |
| 400 to 450 | 552 | 1676.408 | 0.2401967343189206E-08 |
| 450 to 500 | 690 | 2213.975 | 0.3126077852603632E-08 |
| 500 to 550 | 1026 | 3188.870 | 0.4437616827217346E-08 |
| 550 to 600 | 1334 | 4151.545 | 0.5694480678043083E-08 |
| 600 to 650 | 1574 | 5806.203 | 0.7850782926742040E-08 |
| 650 to 700 | 1721 | 5564.284 | 0.7417382664650155E-08 |
| 700 to 750 | 1842 | 6189.738 | 0.8135382156671757E-08 |
| 750 to 800 | 2257 | 10466.65 | 0.1356502874878124E-07 |
| 800 to 850 | 2325 | 9163.976 | 0.1171242144870846E-07 |
| 850 to 900 | 2237 | 7757.214 | 0.9776967297505460E-08 |
| 900 to 950 | 2309 | 7845.704 | 0.9754818824792728E-08 |
| 950 to 1000 | 2588 | 12797.74 | 0.1558579959154532E-07 |
| 1000 to 1050 | 2360 | 7361.207 | 0.8906840929941927E-08 |
| 1050 to 1100 | 2069 | 5537.271 | 0.6610339983129161E-08 |
| 1100 to 1150 | 1864 | 2972.150 | 0.3500993347246819E-08 |
| 1150 to 1200 | 1722 | 2419.010 | 0.2811831303721698E-08 |
| 1200 to 1250 | 1637 | 1681.589 | 0.1929037614608955E-08 |
| 1250 to 1300 | 1628 | 2127.983 | 0.2409326090255036E-08 |
| 1300 to 1350 | 1651 | 1904.722 | 0.2128642127092016E-08 |
| 1350 to 1400 | 1725 | 2608.485 | 0.2877662584286514E-08 |
| 1400 to 1450 | 1961 | 5441.608 | 0.5926458285249746E-08 |
| 1450 to 1500 | 2207 | 8900.669 | 0.9570679535567579E-08 |
| 1500 to 1550 | 1935 | 4855.020 | 0.5154641935063285E-08 |

Debris Samplings for Satellites (Continued)

| Band (km) | No. Objects | Obj hr/day | Spatial Density (obj/cu km) |
|--------------|-------------|------------|-----------------------------|
| 1550 to 1600 | 1721 | 2395.986 | 0.2511967004175655E-08 |
| 1600 to 1650 | 1603 | 1760.118 | 0.1822333409955099E-08 |
| 1650 to 1700 | 1524 | 1626.569 | 0.1663216476889449E-08 |
| 1700 to 1750 | 1415 | 1141.005 | 0.1152359437392957E-08 |
| 1750 to 1800 | 1341 | 913.4477 | 0.9112568714450620E-09 |
| 1800 to 1850 | 1270 | 760.1544 | 0.7491150628152655E-09 |
| 1850 to 1900 | 1219 | 667.5206 | 0.6498800420394691E-09 |
| 1900 to 1950 | 1170 | 584.1207 | 0.5618558241441207E-09 |
| 1950 to 2000 | 1134 | 541.4126 | 0.5145607186040955E-09 |
| 2000 to 2050 | 1093 | 535.1542 | 0.5025771598361100E-09 |
| 2050 to 2100 | 1048 | 493.4404 | 0.4579368856310043E-09 |
| 2100 to 2150 | 973 | 362.0212 | 0.3320338952900740E-09 |
| 2150 to 2200 | 907 | 233.6187 | 0.2117695391357762E-09 |
| 2200 to 2250 | 877 | 174.9677 | 0.1567656950509192E-09 |
| 2250 to 2300 | 869 | 160.5325 | 0.1421748141901380E-09 |
| 2300 to 2350 | 856 | 134.6452 | 0.1178815884591715E-09 |
| 2350 to 2400 | 852 | 124.5987 | 0.1078432372894129E-09 |
| 2400 to 2450 | 849 | 125.4796 | 0.1073754485770044E-09 |
| 2450 to 2500 | 846 | 120.8707 | 0.1022665678956541E-09 |
| 2500 to 2550 | 840 | 100.6126 | 0.8417305210199332E-09 |
| 2550 to 2600 | 837 | 94.76492 | 0.7839782985182263E-09 |
| 2600 to 2650 | 835 | 96.89417 | 0.7927145790290852E-09 |
| 2650 to 2700 | 834 | 90.23243 | 0.7300816296625897E-09 |
| 2700 to 2750 | 832 | 85.59013 | 0.6849336740589221E-09 |
| 2750 to 2800 | 844 | 188.2970 | 0.1490426371665348E-09 |
| 2800 to 2850 | 838 | 101.4034 | 0.7939402678987912E-10 |
| 2850 to 2900 | 837 | 89.19577 | 0.6908333493569969E-10 |
| 2900 to 2950 | 840 | 85.44997 | 0.6547267688838157E-10 |
| 2950 to 3000 | 844 | 80.81250 | 0.6125915475806957E-10 |
| 3000 to 3050 | 843 | 76.78901 | 0.5758572201360424E-10 |
| 3050 to 3100 | 846 | 81.87234 | 0.6075644637405624E-10 |

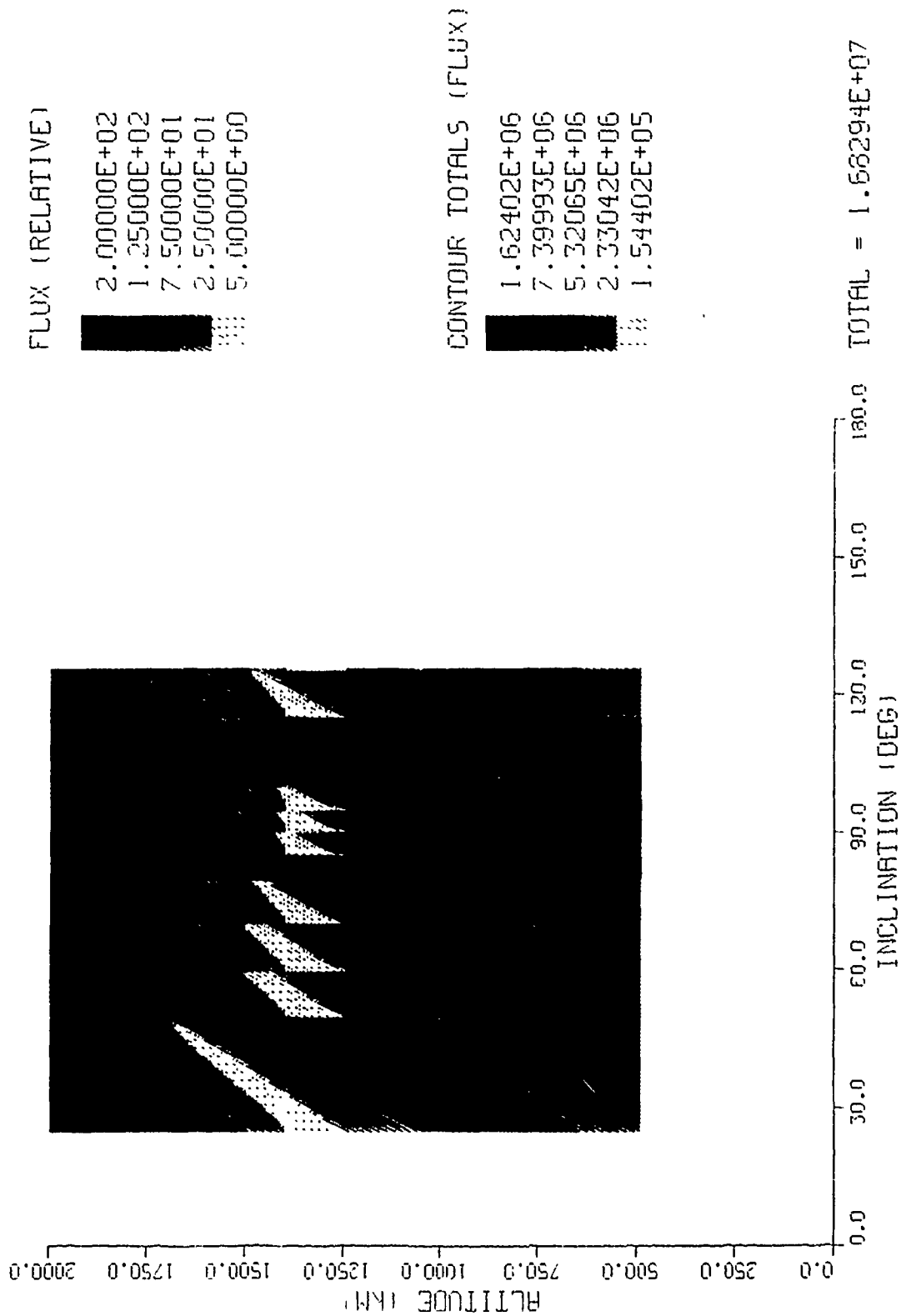
Debris Samplings for Satellites (Continued)

| Band (km) | No. Objects | Obj hr/day | Spatial Density (obj/cu km) |
|------------------|--------------------|-------------------|------------------------------------|
| 3100 to 3150 | 849 | 85.61419 | 0.6286643900307874E-10 |
| 3150 to 3200 | 851 | 88.00147 | 0.6394477078822938E-10 |
| 3200 to 3250 | 855 | 89.45557 | 0.6432625671789372E-10 |
| 3250 to 3300 | 858 | 88.06644 | 0.6267301979278323E-10 |
| 3300 to 3350 | 863 | 105.8137 | 0.7452893280968370E-10 |
| 3350 to 3400 | 862 | 118.4621 | 0.8258435679102947E-10 |
| 3400 to 3450 | 866 | 124.4817 | 0.8589788677873132E-10 |
| 3450 to 3500 | 863 | 112.3143 | 0.7671728644880264E-10 |
| 3500 to 3550 | 867 | 130.3320 | 0.8812772070344463E-10 |
| 3550 to 3600 | 870 | 130.5947 | 0.8742043083044551E-10 |
| 3600 to 3650 | 872 | 165.4352 | 0.1096384038516520E-09 |
| 3650 to 3700 | 883 | 306.4097 | 0.2010511627158161E-09 |
| 3700 to 3750 | 882 | 235.7542 | 0.1531630885711374E-09 |
| 3750 to 3800 | 868 | 122.2742 | 0.7865774564548039E-10 |
| 3800 to 3850 | 861 | 112.1764 | 0.7145644318044893E-10 |
| 3850 to 3900 | 859 | 104.9593 | 0.6620861815572869E-10 |
| 3900 to 3950 | 856 | 110.7757 | 0.6920109823800033E-10 |
| 3950 to 4000 | 849 | 80.18132 | 0.4960627223005597E-10 |
| 4000 to 4050 | 845 | 73.74618 | 0.4518748834388251E-10 |
| 4050 to 4100 | 841 | 72.88008 | 0.4423060674991847E-10 |
| 4100 to 4150 | 840 | 67.09614 | 0.4033358334382498E-10 |
| 4150 to 4200 | 841 | 72.17503 | 0.4297651528475500E-10 |
| 4200 to 4250 | 841 | 98.96992 | 0.5837701197205649E-10 |
| 4250 to 4300 | 838 | 88.89803 | 0.5194508582761376E-10 |
| 4300 to 4350 | 833 | 61.86168 | 0.3581021451482455E-10 |

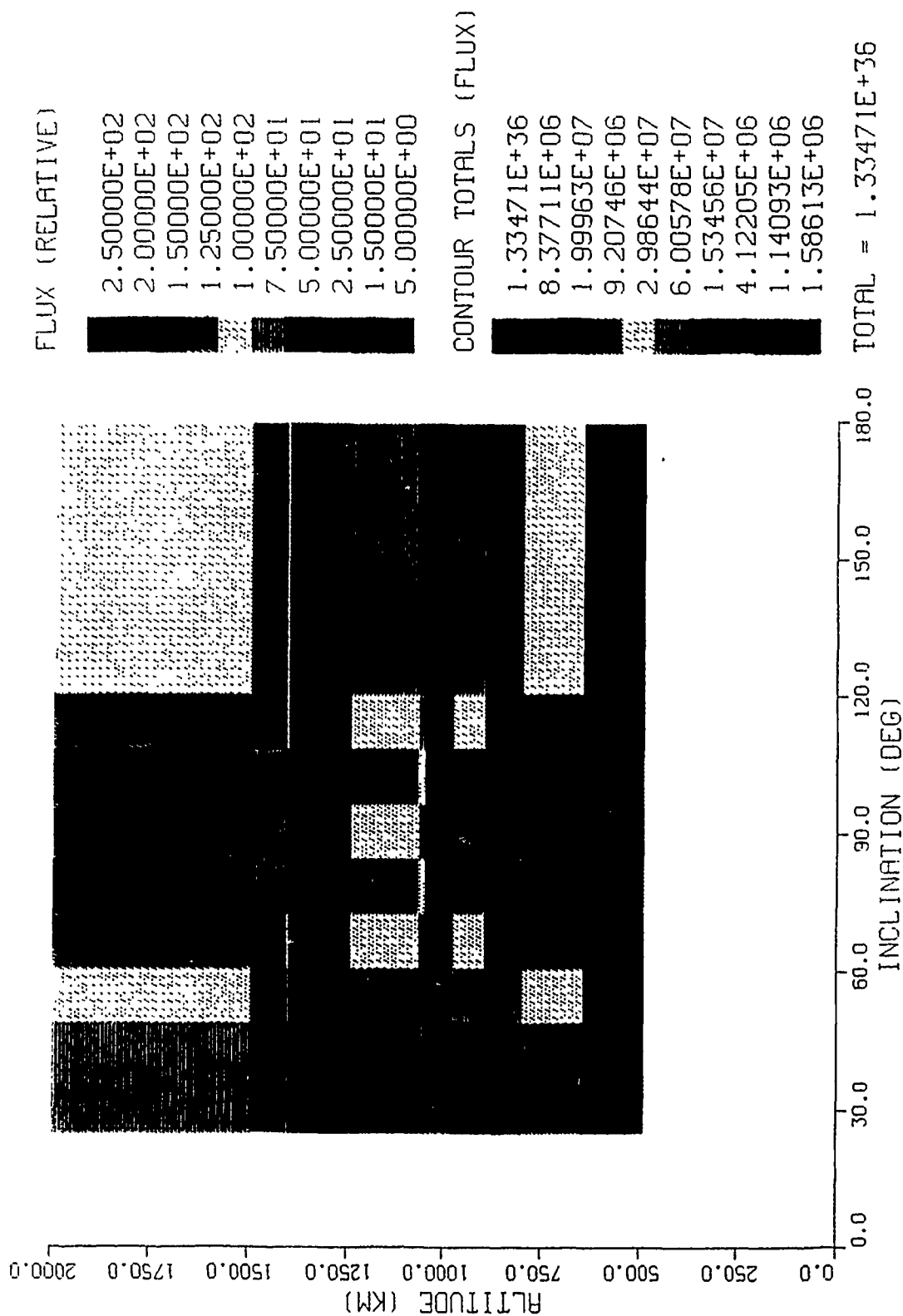
APPENDIX D

DIFFERENT CONTOUR PLOT ATTEMPTS (ALT vs INCLINATION)

SPACE DEBRIS FLUX



SPACE DEBRIS FLUX



SPACE DEBRIS FLUX

